Atmospheric Soundings in Near Real Time from Combined Satellite and Ground-Based Remotely Sensed Data

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INTRODUCTION

The mobile profiling system (Profiler) has been upgraded from that described by Wolfe et al (1995). It combines ground based instruments, including a five beam 924 MHZ radar wind profiler, a Radio Acoustic Sounding System (RASS), a passive microwave sounder, with a receiver and processor for meteorological (met) satellite data. With appropriate met satellite input it can probe the atmosphere from the surface to over 30 km. The upgrades include a new antenna that combines the wind radar and RASS, and a newer, better designed shelter housing the processors and other electronics. These and other improvements have led to a more robust system that is easier to transport and set up.

The method for combining these data is not site specific and requires no *a priori* information. The merging method provides soundings with an accuracy in temperature (or virtual temperature) relative to rawinsonde soundings at least equal to other currently published methods. Data at the lower satellite sounding altitudes are modified based on measured values from the ground based sensors. However, the wind velocity accuracy above the maximum radar data level is limited by inaccuracies in current methods of deriving wind velocity from satellite data. New ways to derive satellite wind velocities are being investigated. In the interim, we have the option of merging data from rawinsondes, where the latter system provides data for higher levels, adjusted to take into account changes in profiles of wind and other variables detected by the ground based remote sensors since the rawinsonde launch. The Profiler maybe used for detailed analysis of meteorological variables for research and operations over mesoscale areas (e.g., pollution studies and severe storm forecasting), plus a number of military applications. It has operated successfully in several different climates: the Los Angeles Free Radical Experiment at Claremont, CA, tests at White Sands Missile Range, NM; Erie, CO; Wallops Island, VA; and other sites.

SYSTEM DESCRIPTION

Wolfe, etal(1995) and Cogan (1995) describe the earlier configuration of the Profiler in some detail. Here we emphasize improvements to the system implemented during the past year and planned for the first few months of 1997.

A new antenna system combines the wind profiling radar with the RASS, thereby eliminating the need for separate RASS units. The acoustic portion of the phased array RASS consisting of 120 sound transmitter elements points into the wind at an elevation and azimuth angle as determined by the wind speed and direction measured by the radar profiler. By slightly tilting into the wind the sound waves will be over the radar (except at very high wind speeds). Current sytems use four separate RASS arrayed around the radar to insure that at least one will be upwind. The acoustic phase front may have a slight tilt, but turbulence will tend to wash out any noticeable effect. The radar operating at 924 MHZ can provide wind profiles as often as once every 3 or 4 minutes with a vertical resolution of 100 m up to a height of 3-5 km on average, depending on atmospheric conditions. Under certain atmospheric conditions (i.e., moist and turbulent) heights over 6 km are possible. The RASS can produce soundings of virtual temperature (T_v) up to around 0.8 -1.6 km, again depending on atmospheric conditions, at a vertical resolution of about 100 m. A microwave radiometer operating in the oxygen band from 50-60 GHz is able to produce useful temperature (T) profiles to an altitude of around 3-5 km. A second radiometer produces estimates of total water content (vapor and liquid). These older radiometers are being phased out and replaced by a single radiometer in a package smaller than either of the older ones. Preliminary evaluations show a significant improvement in T accuracy. The Profiler has certain elements in common with fixed-site systems described by Parsons et al. (1994) and Stokes and Schwartz (1994), but has a number of additional features, These additions include software for processing and quality control of data from the ground-based sensors (e.g., Merritt, 1995), and for combining satellite soundings with ground-based profiles in near real time.

The merging algorithm applies no matter where the Profiler is located; i.e., it is not site specific and requires no a priori information. The microwave radiometer, however, uses a statistical retrieval method that is site specific. Previous methods for merging satellite and other data (Westwater et al., 1984a, 1984b; Schroeder et al. 1991) to retrieve profiles of T (or Tv) required site specific statistical data.

A new algorithm calculates a satellite sounding for the location of the Profiler instead of simply using the nearest one (Spalding, 1996). The algorithm fits a plane to the nearest three soundings at each pressure level for each variable. Interpolation of a value of a given variable is performed when the Profiler lies within the boundary of the triangle defined by the three satellite sounding locations. The routine extrapolates values for Profiler locations within a short distance outside of the triangle (e.g., 50 km). Beyond that "extrapolation distance" the program reverts to the older method of using the nearest sounding, if the distance does not exceed a user determined maximum (e.g., 300 km). This type of situation could occur, for example, when atmospheric conditions or some instrument error severely limited the number of "good" satellite soundings, or the Profiler is positioned outside the swath of the particular satellite pass. These distances are used for determination of the weight to be given to the satellite values when the lower sounding heights "overlap" the upper part of the ground-based profiles. The procedure for merging the ground based and satellite profiles sets the distance to the Profiler to O km when the Profiler lies within the larger triangle defined by the three closest soundings plus the extrapolation distance. The actual distance is used when the nearest sounding method is required. To determine the best pass for merging we add a "time distance" to the spatial distance to account for data "staleness." Presently we calculate the time distance at 30 km/hr. The best pass is considered to be the one with the least time-space distance.

Neural net methods under development will provide the Profiler with more rapid retrievals of satellite soundings of temperature and possibly other meteorological variables. Bustamante, et al (1997), also in these Proceedings, provide a description of the neural network for retrieval of temperature profiles. Some benefits of a neural net approach include the elimination of the need for first guess profiles for each inversion and a faster retrieval process. Faster running inversion software should mean the ability to apply the soundings closer to real-time than currently possible. Also, these methods can easily run on current and planned Profiler processors.

'TEST RESULTS

The Profiler has generated soundings for several field experiments and system tests in different climatic regions. Examples include Claremont, CA; White Sands Missile Range, NM; Erie, CO; Wallops Island, VA; and other sites. Some of the results are described in Wolfe, et al (1995) and Cogan (1995). Here we summarize a few of these earlier results and present new data that also show potential application to mesoscale analysis and forecasting. Wolfe, et al (1995) and Cogan (1995) also present color charts showing time vs. height wind barb plots of wind velocity from some of the aforementioned test sites.

Personnel from ARL and ETL participated in the LAFRE, using the Profiler to obtain detailed sounding data for the California Air Resources Board. These data also served to check out the system and algorithms. The system operated almost continuously from 28 August 1993 through 23 September 1993. From 28 August through 11 September 1993 the Los Angeles basin was under a strong upper ridge, at times a closed high pressure area from the surface through 300 hPa. The marine boundary layer was consistently capped by one or more inversions. Wolfe et al. (1995) and Cogan (1995) present charts that show wind velocities from the radar profiler for typical days during this early part of the LAFRE, depicting light and often variable winds. Combining these profiles with the nearest useful satellite sounding, sometimes as much as 300 km distant, led to a "worst case" situation on several days, in that atmospheric conditions, especially wind velocity, are often quite different 200 or 300 km to either side of a strong ridge.

Table 1, derived from data in Cogan and Wolfe (1995), shows mean and standard deviation of wind speed differences in ins-l for the radar profiler and the satellite (adjusted at lowest three satellite data levels) relative to rawinsonde during part of the LAFRE. The maximum number of data comparisons was 36 over the first period (five days) compared with a maximum of 12 over the seven days of the second period. Cogan and Wolfe (1995) also presented data from the LAFRE that suggested that for combined soundings the mean and standard deviation of T_v differences were about $\pm$ 0.4 and 1 to 1.5 K, respectively.

TABLE 1. Means and averages of 0.1 km standard deviations of wind speed differences (ms-1) for 0.3 km layers (indicated sensor vs. rawinsonde). Radar= radar wind profiler, Sat= Satellite.

Mean Radar	Mean Sat	Standard Deviation Radar	Standard Deviation Sat	Layers Radar	Layers Sat	Dates (Sept, 1993)
0.75	10.84	1.88	8.60	14	6	7-11
1.53	8.61	2.75	2.88	11	6	17-23

At times rawinsonde data may contain serious errors. Fisher et al. (1987) present information on the average errors found in several types of rawinsonde systems. To gain an idea of the quality of the rawinsonde data at the LAFRE, soundings were compared from two similar systems (MARWIN and CLASS) receiving data from one sonde. Differences in T_v from comparisons using a single sonde averaged around $\pm$ 0.2 to 0.4 K, with maximum differences of about $\pm$ 1 K. Cogan and Wolfe (1995) compared wind speed differences between the two systems. Their figure 2 showed a periodic pattern that is consistent with other data examined to date. The large differences of up to 3 ins-l near and above 3 km were on the high side, but values around $\pm$ 1 ins-l were not uncommon. Cogan (1995) presented data showing a few wind direction variations of > 90 ° in one case during the LAFRE, although wind direction differences for most of the 100 m layers in data examined to date were < 10 °. This type of comparison suggests that differences in Profiler wind speed and direction of around $\pm$ 1 ins-l and 100, respectively, relative to rawinsonde may be close to the "best" one could expect. A possible partial explanation for the wind speed differences is that the MARWIN software has more extensive built-in checks and somewhat smoothes the data.

A test of the Profiler at the NASA Wallops Flight Facility (WFF) on Wallops Island, VA, provided the opportunity to compare wind profiles for the lowest 1.9 km with those obtained from radar-tracked pibal balloons. An unusual aspect of this experiment as compared with other similar studies (e.g., Weber and Wuertz 1990) was the ability to examine the background wind variability at the same time as the comparisons. During the week of 17-21 July 1995, for morning and afternoon periods lasting about 1 to 1-1/2 h, two pibals were launched about 3 min apart every 15 min (four to five "pairs" each period). The Profiler operated continuously during these periods with the capability of producing wind profiles every 3 min. A 3 min sounding was generated starting prior to the second pibal of each pair. The Profiler sounding was compared with the profile from the second pibal of each pair, and comparisons were made between the two pibals. Surface values shown were taken from the WFF and Profiler surface sensors. The site of the experiment was about 0.2 km west of the ocean, with the Profiler located < 50 m east from the pibal launch site. Tables 2 and 3 present the means and standard deviations of the wind speed . . and direction differences between Profiler and pibal, and similar values from concurrent pibal "pairs" during 18 July (eight "pairs"), 20 July (nine "pairs"), and 21 July 1995 (five "pairs"). These tables show values for 100 m layers averaged from the surface to 1.9 km.

TABLE 2. Means and standard deviations of differences of wind speed between Profiler (3 min. averages) and **pibal**, and between **pibals** 3 **min** apart. Averages of 100 m layer values shown, for the surface through 1.9 km.

Day (July 1995)	Number of comparisons	Mean (in^{s}l) Profiler vs. Pibal	Mean (in^{s}l) Pibal vs. Pibal	Standard Deviation (in^{s}l) Profiler vs. Pibal	Standard Deviation (in^{s}l) Pibal vs. Pibal
18	8	-0.70	0.00	0.91	0.63
20	9	-0.31	-0.01	0.69	0.84
21	5	-0.36	-0.09	0.92	0.65

TABLE 3. Means and standard deviations of differences of wind direction between Profiler (3 min. averages) and **pibal**, and between **pibals** 3 min apart. Values in parentheses are for z $\geq$ 300 m. Averages of 100 m layer values shown, for the surface (or 300 m) through 1.9 km.

Day (July 1995)	Number of comparisons	Mean (deg) Profiler vs. Pibal	Mean (deg) Pibal “vs. Pibal	Standard Deviation (deg) Profiler vs. Pibal	Standard Deviation (deg) Pibal vs. Pibal
18	8	19.14 (18.92)	-0.31 (1.25)	13.00 (9.72)	9.53 (5.67)
20	9	7.13 (4.46)	-0.66 (-1.08)	8.56 (8.55)	8.13 (8.30)
21	5	11.71 (9.00)	0.64 (0.65)	3.96 (3.86)	4.21 (3.01)

The Profiler vs. **pibal** comparison for 18 July showed significantly greater differences in wind direction than for the other two comparison days (20 and 21 July). The **pibal** vs. **pibal** comparison for that day also showed somewhat larger differences in the standard deviation of wind **direction** relative to those for the other days. The standard deviation of wind direction differences (100 m layers) exceeded 100 for **pibal** vs **pibal** for heights (z) $\leq$ 0.3 km and z = 1.1 **km**, and for the Profiler vs. **pibal** at z $\leq$ 0.8 km and z = 1.2 km. The magnitude of mean differences in wind direction between Profiler and **pibal** was $\geq$ **20 °** at z = 0.6 **km**, 0.8 $\leq$ z $\leq$ **1.2** km, and 1.5 $\leq$ z $\leq$ 1.8 km (maximum of about250 at 1.6 km). On this day the **pibals** traveled eastward, passing over the ocean within a minute**after** launch. These larger differences were not unexpected since the **pibals** drifted over the ocean after reaching 200 or 300 m in altitude, leaving the highly convective conditions that existed over the land. Later in the afternoon small, but intense, thunderstorms passed through from the west, forcing the test to be canceled before 1500 EDT (1900 UTC) due to the danger of lightning strikes.

The largest direction difference between the Profiler and **pibal** was at the “surface” (about 5 m AGL) for the latter two days and at 0.1 km on 18 July. Both systems relied on surface stations separated by about 10 m horizontally and 1-2 m vertically (the WFF anemometer was higher). The location only about 200 m **from** the ocean and the mix of land and water surfaces near the launch site may account for much of the observed direction differences in the lowest 0.1 to 0.2 km. The balloons drifted off roughly to the northwest except on 18 July, soon **after** turning toward the east to northeast, passing over the northern half of the island, and out over the water. Since the ascent rate of the **pibals** was about 5 ins-l and the average wind speed for most of the test periods was about 5 to 7 ins-l during much of each ascent, the balloon ended up about 2 to 3 km from the Profiler and **pibal** launch site by the time it reached an altitude of 2 km. On 21 July the wind speed at most heights exceeded 10 in^{s}l, causing the **pibal** to **drift** about 4 km by the time it rose to 2 km.

The variations between profiles from **pibals** launched 3 **min** apart were not insignificant, and on occasion exceeded those between Profiler and **pibal**. These results support the idea that differences between radar profiler and rawinsonde wind soundings in earlier data (e.g., Weber et al, 1990) may be partly a result of real atmospheric temporal and spatial variation.

FUTURE WORK

Several initiatives are planned for the near **future**. One involves a better extraction of satellite temperature wind velocity profilers using neural network methods as noted above. **Bustamante**, et **al** (1997) present work **performed** in 1996 and earlier on retrieval of temperature soundings, and note planned work on improved temperature profiles and wind velocity estimation. Initial results on wind velocity should begin to appear within a year. Also, the software for fitting a satellite sounding for the location of the Profiler should help improve accuracy. The new antenna that combines the radar and **RASS functions** shows promise in improving the ground based profiles of both wind and virtual temperature. An early test at Erie, CO provided profiles to 4.1 km (maximum height for radar parameters used) during conditions of light snow. Additional tests are planned at **WSMR**, NM that will give a more complete indication of performance of the system with the new antenna. **After** installation of new, higher power, amplifiers in February-March 1997 the tests will continue. The additional power should increase performance **further**.

The new, passive, microwave radiometer has run in a test mode, but has not been integrated into the Profiler. However, comparisons between radiometer output and rawinsonde data at Wallops Island, VA and **WSMR**, NM suggest a marked improvement over the older, larger radiometer for heights **> 0.5** km. Root Mean Square **(RMS)** differences between radiometer temperatures and those from rawinsonde were about 1 K for $z \leq 1.2$ km (< 0.5 K near 0.2 km) over 9 comparisons at Wallops Island. These values compare favorably with those reported by Moran and **Strauch** (1 994) for comparisons between RASS and rawinsonde. For $1.2 < z \leq 3$ km the **RMS** differences were ≤ 1.6 **K**, greater than values reported by Moran and **Strauch** (1994), but within stated requirements. If confirmed in ongoing tests, the radiometer may supplant the RASS, thereby allowing for a smaller, more portable Profiler.

ETL plans to introduce new software for improved control and data processing for the “- radar and RASS during the spring of 1997. This **software** will consist of “standard” architecture and coding, and eliminate the necessity of special signal processing boards. It will allow easier control by the user, and potentially “hands of^{f} operation by non-specialists. This software package will be integrated into the Profiler during the ongoing **re-configuration** into a smaller, more mobile system.

The next version of the Profiler will have the processors in a shelter suitable for a High Mobility Multi-Wheeled Vehicle (HMMWV) instead of a towed, enclosed trailer. A newer, more compact receiver and processor for meteorological satellites (both NOAA and DMSP) currently being integrated into the present system also will reside in the shelter. Two small enclosed tracking antennas (0.46 m flat plates) will soon replace the present much larger enclosed tracking antenna (1.2 m dish). The combined size and weight of the newer antennas are less than the one older one. The lower size and weight of the microwave radiometer now undergoing evaluation will allow it to fit easily on the new system. The upgraded software is being reworked to fit as close as possible to Army common hardware and software standards. Lightweight Computer Unit (LCU) computers, or equivalent civilian PC's (e.g., 200 MHZ Pentium computers), will replace the current mix of workstations and PC's. The resulting Profiler "platform" will consist of a standard shelter on a HMMWV or equivalent vehicle that will tow a smaller trailer containing the radar antenna.

CONCLUSION

An upgraded Profiler prototype is being developed to answer Army requirements as stated in the approved Profiler ORD and MNS. This system will provide a means of collecting data from a variety of profiling instruments and merging those data into combined meteorological soundings for near real time operational uses. The data provided by the MPS will have a variety of military and civilian applications. The MPS can provide timely support for airfield operations, giving, for example, near real time indications of potentially hazardous wind conditions. Mesoscale models will have access to detailed, very rapid refresh, atmospheric soundings within and somewhat above the boundary layer. Through access to data from environmental satellites, and potentially from UAV sensors and dropsondes, the Profiler will obtain meteorological data throughout the domain of a mesoscale model. The ability to generate a picture of very short-term flow and virtual temperature patterns in the lower troposphere can lead to a better understanding of the atmosphere and to better modeling at smaller scales. As the Los Angeles Free Radical Experiment showed, this type of system can be invaluable for pollution studies.

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